AD-A077 071 AEROSPACE CORP EL SEGUNDO CA MATERIALS SCIENCES LAB F/G 9/5
DEVELOPMENT OF A PARTIAL-DISCHARGE DETECTION SYSTEM FOR TRAVELI--ETC(U)
SEP 79 F HAI , K W PASCHEN F04701-78-C-0079
UNCLASSIFIED TR-0079(4402)-3 SAMSO-TR-79-40 NL

1 OF 1
AD-
A077071

END
DATE
FILMED
12 79
DDC

REPORT SAMSO-TR-79-40

LEVEL II

(12)

AD A077071

Development of a Partial-Discharge Detection System for Traveling-Wave-Tube Testing

F. HAI AND K. W. PASCHEN
Materials Sciences Laboratory
Laboratory Operations
The Aerospace Corporation
El Segundo, Calif. 90245

28 September 1979

Interim Report

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED

Prepared for

SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
Los Angeles, Calif. 90009

This interim report was submitted by The Aerospace Corporation, El Segundo, CA 90245, under Contract No. F04701-78-C-0079 with the Space and Missile Systems Organization, Deputy for Space Communications Systems, P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009. It was reviewed and approved for The Aerospace Corporation by W. C. Riley, Director, Materials Sciences Laboratory and H. E. McDonnell, Principal Director, COMSATS Directorate, Satellite Systems Division. Major C. J. Kennedy, SAMSO/SKX, was the project officer for Advanced Space Programs.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Clarence J. Kennedy

C. J. Kennedy, Major, USAF
Project Engineer

Gaal L. Fjetland

G. L. Fjetland, Major, USAF
Acting Director, Advanced Space Communications Capabilities

FOR THE COMMANDER

Forrest S. McCartney

F. S. McCartney, Brig. Gen., USAF
Deputy for Space Communications Systems

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19 REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 18 SAMSO-TR-79-40	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 DEVELOPMENT OF A PARTIAL-DISCHARGE DETECTION SYSTEM FOR TRAVELING-WAVE-TUBE TESTING.		5. TYPE OF REPORT & PERIOD COVERED 9 Interim rept. 6. PERFORMING ORG. REPORT NUMBER 14 TR-0079(4402)-3
7. AUTHOR(s) 10 Francis Hai ~~and~~ Kenneth W. Paschen		8. CONTRACT OR GRANT NUMBER(s) 15 F04701-78-C-0079
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Aerospace Corporation El Segundo, Calif. 90245		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Space and Missile Systems Organization Air Force Systems Command Los Angeles, Calif. 90009	11	12. REPORT DATE 28 Sep[redacted]79 13. NUMBER OF PAGES 45
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) 12 53		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Corona Effects
High-Voltage Defects
Hi Pot testing
Partial Discharge
Traveling Wave Tubes

403 644 Gu

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The development of a test system ~~designed by The Aerospace Corporation~~ to detect and monitor partial discharges (PD) in a traveling wave tube (TWT) is described. The assembled system is capable of monitoring discharges of a magnitude ranging from 0.25 pC to above 250 nC. During this operation, the TWT can be subjected to pressures ranging from atmospheric to below 10^{-5} Torr and to temperatures ranging from -20 to +90°C. Developmental studies, which included the analysis of various test circuits and the examination of test circuit calibration that resulted in the present test system are

see next page

DD FORM 1473 (FACSIMILE)

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

,01

19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

reported. Investigations in addition to the TWT tests that have been conducted with this system are discussed. For long-term testing of TWTs, a microprocessor-controlled PD test system is proposed.

PREFACE

The authors are greatly indebted to F. M. Wachi for encouragement and support of this project and the test program.

CONTENTS

FIGURES

I. INTRODUCTION

Recent high-voltage (HV) failures of traveling wave tubes (TWTs) undergoing long-term thermal-vacuum exercising and qualification testing emphasize the need for a test method that can detect an existing or latent high-voltage defect early in fabrication and in testing. Although the present TWT qualification procedures do include high-voltage tests that electrically and environmentally stress the TWT above operational levels, with these tests, together with their pass-fail criteria, apparently it is not possible to detect tubes that will eventually fail, as evidenced by failures on the test rack and the suspected high-voltage failures in space.

The following efforts were conducted to gain a thorough understanding of the requirements that must be placed on any new or improved test technique: (1) All available TWT high-voltage failure analyses were reviewed to identify failure mechanisms. (2) High-voltage test methods currently used by the TWT manufacturers were examined, and the applicability and limitations of each were noted with respect to the possible failure mechanisms. (3) Since high-voltage failure in electrical systems has been a subject of interest and investigation for several decades, pertinent information covering both test results and techniques from the open literature and directly from several specialists in the field was reviewed. (4) Corona detection devices that are commercially available from several manufacturers were evaluated with respect to applicability and capability.

All high-voltage failure analyses that have been performed to date indicate that failure is a result of a breakdown of the polymer encapsulation system of the TWT. In most of the cases, this breakdown occurred at the polymer potting-ceramic interface, although in one or two cases, the breakdown occurred in the bulk potting. In all these cases, the defect was electrically detected in a late or final phase of failure and later confirmed by destructive examination. Detection of the defect at the initial phase was not the objective in the high-voltage tests and could not be performed with the instrumentation that was used. However, detection of all high-voltage defects at this early stage is essential to prevent failures during space applications that were initiated or were in an early stage during the final phase of high-voltage testing. Therefore, a primary requirement of the technique to be developed is that it have an early detection capability, which dictates a system that is highly sensitive to high-voltage defects. The TWT is subjected to long-term thermal vacuum cycling and high-voltage testing for screening purposes. This technique is expected to accelerate the growth of any minor defect and initiate the growth of any latent defects in the encapsulation system. Also, diagnostic test signals that might indicate a high-voltage defect may be enhanced under certain thermal-vacuum conditions. Therefore, the system to be developed must also have a thermal-vacuum test capability.

The review of various techniques including acoustical, optical, and electro-optical methods that have been or are being used to detect defects in polymer insulation (mainly voids in polymer materials) indicates that only the electrical test method, i.e., the partial discharge (PD) detection method, has the sensitivity and the general applicability to be of use in testing TWTs or TWT components. The survey and examination of several PD detection systems that are commercially available indicate comparable capabilities and sensitivities. A commercial test system was not obtained immediately for TWT testing at Aerospace because of uncertainties concerning the precise level of sensitivity required. A decision was made to develop a PD detection system from laboratory equipment available in the Materials Sciences Laboratory.

In Section II of this report, the PD detection technique is briefly described, and the essential elements of the detection system given. The features of each of two possible arrangements of the PD detection circuit are explained. (Additional information is given in Appendix A.) One of these systems was selected for development. The capabilities and sensitivity required of this system are given.

In Section III, The Aerospace Corporation PD detection system set up for TWT testing is described. The electrical circuit, as well as the physical layout of this system, is given. Thermal-vacuum capabilities are described. (Investigations of several circuit arrangements that determined the design of the present system are described in Appendix B.)

In Section IV are listed some of the measurements that have been obtained. In Section V, the future developmental efforts planned for this system are discussed.

II. PARTIAL-DISCHARGE DETECTION METHOD

Minute voids, cracks, and separations in the encapsulation system of the TWT can result from poor fabrication techniques, extreme environmental stresses, and long-term operation. These cavities, under appropriate electrical stress, can exhibit corona-like discharges. (These discharges are usually referred to as partial discharges (PD) to indicate that they extend across only a part of the distance separating the metal electrodes.) This transient phenomenon provides an electrical means of detecting encapsulation defects because the partial discharges occurring in the defects produce current impulses at the electrodes in contact with the encapsulation.

Placement of the electrode-encapsulation unit (TWT test sample) within the basic PD detection circuit is shown in Fig. 1. The elements of this circuit are: (1) the high-voltage source, (2) the high-voltage-source impedance, (3) the test sample C_t, (4) the coupling capcitor C_{cc}, (5) the detection impedance Z, and (6) a detection system that usually includes amplifiers, filters, oscilloscopes, and counters. The high-voltage source is a corona-free direct-current power supply with variable voltage amplitude up to at least twice the operating voltage of the TWT. The high-voltage source impedance is made large enough to prevent bypass of the PD pulse through the power supply, and the C_{cc} is usually large enough to minimize its impedance to the high-frequency PD pulse. The detection impedance may be either inductive or capacitive; in either case, it is shunted by the capacitance of the connecting cable.

The detection impedance can be placed either in series with the test sample (series detection) or in parallel to the test sample (parallel detection) (Fig. 1). The inherent charge or voltage detection sensitivity of these two arrangements is analyzed in terms of the capacitances of the circuit and is given in Appendix A. This analysis indicates the following:

1. In both arrangements, detection sensitivity decreases with an increase in test-sample capacitance. For small-test-sample capacitance (as in tests of TWTs), the series detection circuit sensitivity is higher than that of parallel detection circuit. For large C_t, the two sensitivities are about equal.

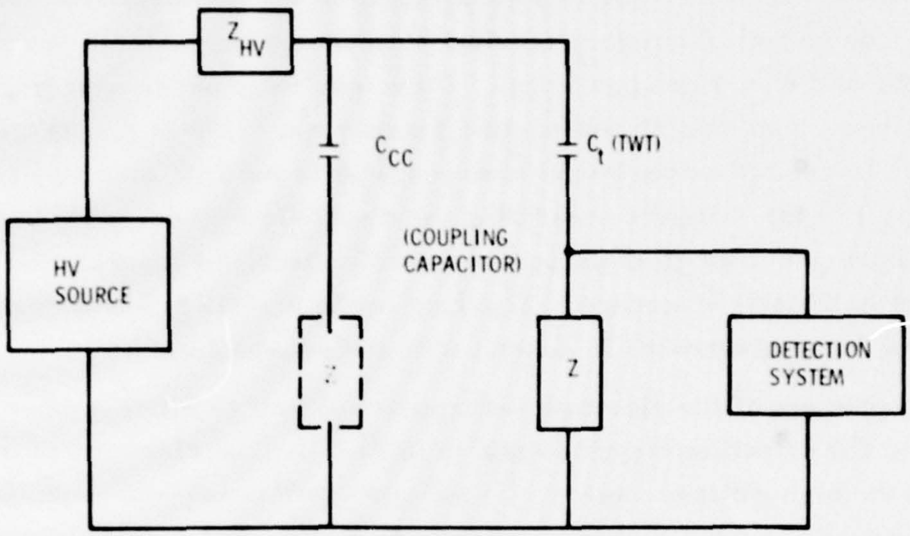


Fig. 1. Basic Partial-Discharge Detection Circuit

2. In both arrangements, sensitivity rapidly increases with increases in coupling capacitance at small C_{cc} values. At large C_{cc} values, sensitivity slowly approaches a finite limit. The charge stored in C_{cc} is dumped through C_t in the event of test sample failure. Therefore, the value of C_{cc} is selected from the standpoints of high-detection sensitivity and minimum damage to the test sample.

3. In both arrangements, the high voltage-to-ground stray capacitance omitted in Fig. 1 must be minimized for high-detection sensitivity.

4. For the case in which $C_t \ll C_{cc}$, as in tests of TWTs, high-frequency noise picked up on the high-voltage section of the test circuit is preferentially shunted to ground through the coupling capacitor. Therefore, placement of the detection impedance in series with the test sample results in lower noise pick up.

On the basis of these considerations, the decision was made to develop a PD detection system with the detection circuit in series with the test sample. However, if required, this system can be converted to the alternative arrangement in which one end of the test sample can be tied directly to ground.

Sensitivity is defined here as the ratio of charge per voltage at the input to the detection circuit to charge per voltage at the terminals of the test sample. This quantity is significant when comparing various test arrangements. However, the quantity that is measured during testing is the output of the detection circuit. The calibration of this output signal therefore is critical for the quantitative measurement of partial discharges. Calibration of several standard PD detection circuits is described in ASTM Standard D 1868-73[1] and IEEE Standard 454-1973.[2] Calibration of the test circuit selected for development by one of the indicated techniques is described in Section III.

---

[1] Standard Method for Detection and Measurement of Discharge (Corona) Pulses in Evaluation of Insulation Systems, ASTM Standard D1868-73, American Society for Testing and Materials (1973).

[2] IEEE Recommended Practice for the Detection and Measurement of Partial Discharges (Corona) During Dielectric Tests, IEEE Standard 454-1973, The Institute of Electrical and Electronics Engineers, Inc., New York (1973).

The essential capabilities and sensitivity required for PD testing of TWTs follow:

Charge Detection Threshold = 1.0 pC

Pressure Range = 10^{-3} Torr to 1.0 atm

Temperature Range = -40 to +90°C

Cylindrical Test Volume = 30 × 50 cm diam

Number of Charge Detection Channels = 3 or more

These specifications, in part, were based on (1) current TWT environmental test conditions, (2) reported PD tests of TWTs, and (3) PD tests performed on other types of systems, e.g., transformers and power supplies. Development of the Aerospace PD system was directed toward achieving these basic capabilities. Other specifications found to be important in tests of TWTs, e.g., a high-level charge (nanocoulomb or microcoulomb) monitoring capability, were incorporated into the system. Additional system features that would facilitate data acquisition and analysis became apparent during the development program and are described in Section V.

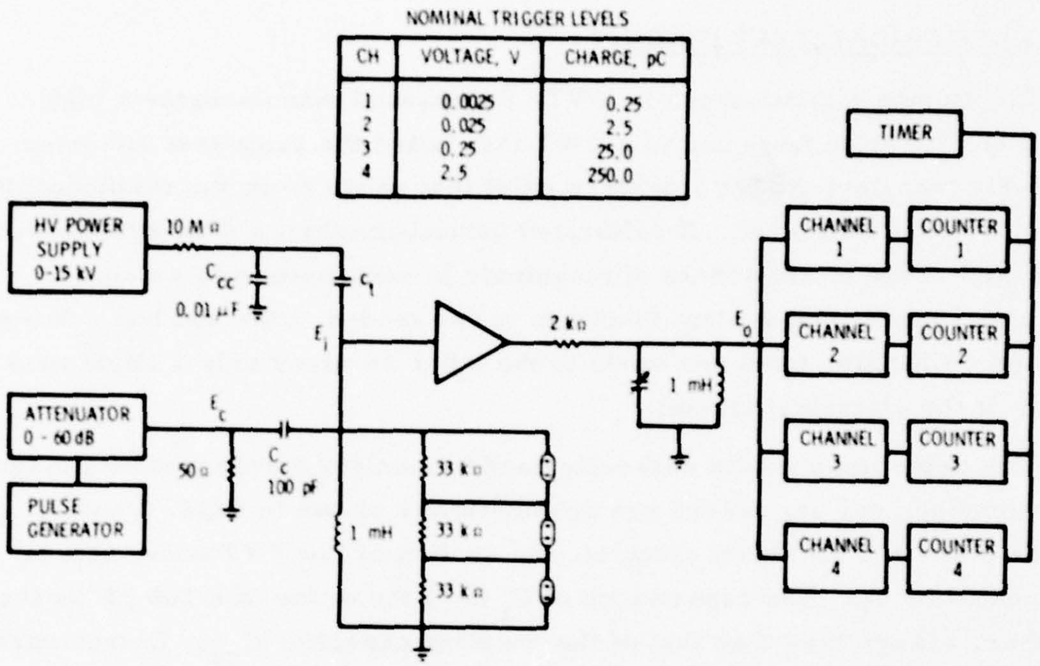
III. THE AEROSPACE CORPORATION PARTIAL-DISCHARGE DETECTION SYSTEM

A. ELECTRICAL TEST CIRCUIT

Monitoring of discharges in TWTs that passed manufacturer's high-voltage qualification tests and in a TWT that failed the same test indicates that highly transient charge transfers exist that range from the subpicocoulomb to the microcoulomb level. A calibrated partial-discharge (PD) system with a minimum range of six orders of magnitude in sensitivity was set up to cover this range. The system functions in two modes, low- and high-charge detection. Changing from one mode to the other requires only a slight modification of the electrical circuit.

The detection circuits currently used to monitor discharges of a magnitude extending over six orders are schematically shown in Figs. 2 and 3. In both the high- and low-level circuits, the section of the TWT under test is represented by C_t. The capacitance of C_t is of the order of a 100 pF or less and, thus, always less than that of the coupling capacitor C_{cc}. Direct-current high voltage is applied to the TWT electrode through a resistance of 10 Mohm, which serves to protect the power supply and to shield the test circuit against transient perturbation in the supply.

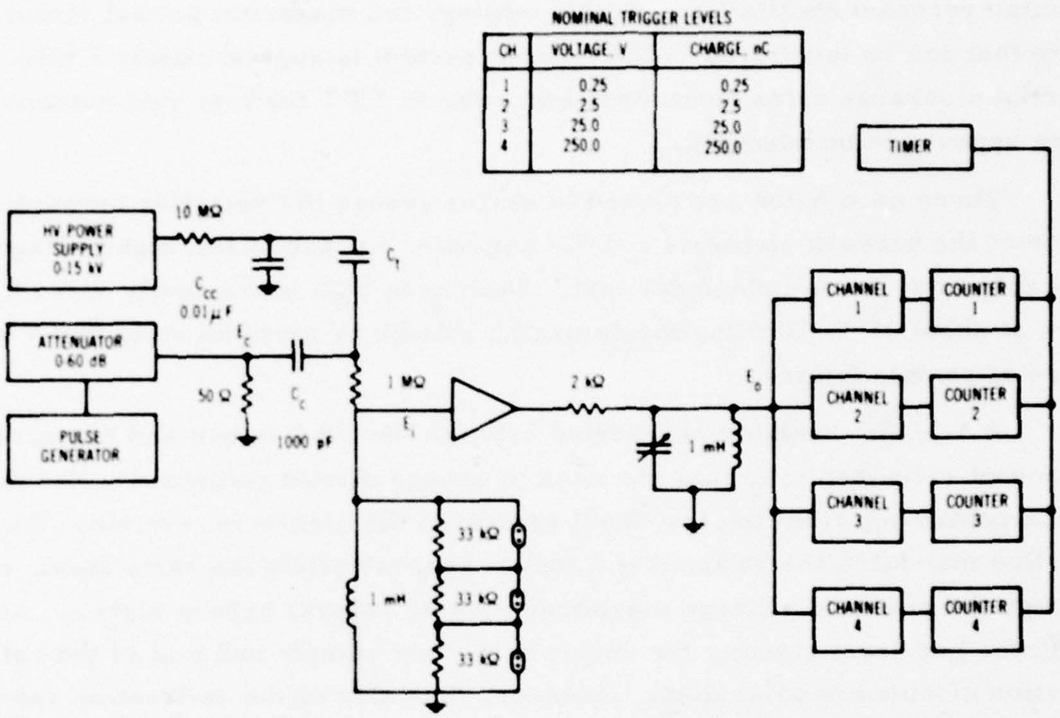
A partial discharge in the test sample C_t will set into oscillation the parallel resonance circuit, which has a 1-mH choke, 100-kohm resistance, and effective parallel capacitance to ground. In the low-level system, this resonance signal is immediately amplified, filtered, and sent into channels with triggers preset at various levels. These levels are calibrated by injecting a fast rise-slow fall pulse into a 100-pF capacitor (Fig. 2), the calibration magnitude being given by the product of the capacitance and the peak voltage. With the trigger levels thus adjusted, each triggering of a particular channel is recorded on the associated counter and correlated with time.



NOMINAL TRIGGER LEVELS

CH	VOLTAGE, V	CHARGE, pC
1	0.0025	0.25
2	0.025	2.5
3	0.25	25.0
4	2.5	250.0

Fig. 2. Low-Level Partial-Discharge Detection Circuit



CH	VOLTAGE, V	CHARGE, nC
1	0.25	0.25
2	2.5	2.5
3	25.0	25.0
4	250.0	250.0

Fig. 3. High-Level Partial-Discharge Detection Circuit

The present four channels are the sweep circuits of two dual-beam Tektronix Type 555 oscilloscopes. The sweep rate on these units is highly set at 20 μsec/div, a rate sufficiently slow to allow complete damping of the excited resonant oscillation. At this setting, the maximum partial discharge rate that can be monitored in the present system is approximately 5 kHz. For partial discharge rates encountered thus far in TWT testing, this maximum rate appears to be adequate.

Three neon bulbs are placed in series across the detection network to protect the network elements and the amplifier in case of full high-voltage breakdown of the sample under test. Each neon bulb is nominally rated to fire at about 95 V, limiting the damaging voltage to approximately 300 V in case of sample failure.

A 1-Mohm resistor is inserted between the TWT output and the parallel resonant circuit to minimize the need to change circuit components and settings when converting from the low-level system to the high-level system. This insertion maintains the resonance signal at approximately the same level, even though the partial discharge magnitude may be several orders higher. As with the low-level circuit, the output of the test sample and that of the calibration circuit are coincident. However, the value of the calibration capacitor in the high-level circuit has been increased to 1000 pF. The pulse-generator peak voltage must cover a range from 2.5 mV to 250 V to calibrate the low- and high-level system for charge transfer ranging from 0.25 pC to 0.25 μC (Figs. 2 and 3).

The detection impedance used in the circuits shown in Figs. 2 and 3 consists of an resistance-inductance-capacitance (RLC) network producing a damped oscillatory signal rather than a resistance-capacitance (RC) network that would produce a singly peaked pulse. The primary advantages of RLC network are higher sensitivity and higher noise immunity as a result of higher input impedance and lower bandwidth, respectively. Another advantage is that the requirement for the calibration pulse shape is less severe (Appendix B). However, the use of a RLC detection circuit requires that the filter circuit be retuned if a new sample is to be tested.

The detection impedance, instead of being in series with the test sample (Figs. 2 and 3), could just as well have been placed in series with the coupling capacitor without significantly affecting detection sensitivity (Appendix B). In fact, for cases in which the test-sample capacitance is larger than that of the coupling capacitor, the impedance is usually placed in series with C_{cc} to reduce the large charging currents. However, in TWT testing, C_t is always much smaller than C_{cc}. In this case, the significant advantage gained by having the detection circuit in series with the sample is that noise picked up on the high-voltage section of the test circuit is reduced, approximately by the ratio of C_t/C_{cc} when compared to the other arrangement (Ref. 2).

Partial discharges are sorted and counted on a four-channel system, where the difference in channel sensitivity is a factor of 10 (Figs. 2 and 3). Partial-discharge spectra, i.e., counts in each of four charge transfer ranges, can easily be derived from data obtained with this system. This procedure appears to be adequate for most of the TWT data taken thus far, where the count rates have been relatively low and the counts concentrated in one or two channels. For more channels, a pulse-height analyzer preceded by a demodulation-pulse shaping circuit can be used in place of the four-channel system.[3] However, a logarithmic rather than a linear amplifier would be required to cover four orders of magnitude in detection sensitivity.

The development of the present PD test circuit is reviewed in Appendix B. The response of the resonant RLC detection circuit is discussed in somewhat more detail. In addition, the importance of the shape of the calibration pulse, with respect to the detection impedance network in use, is examined.

B. TEST SETUP

The present test setup is shown schematically in Fig. 4. The TWT is mounted on the copper base plate that is attached to the lucite cover

---

[3] R. Bartnikas, "Note on Multichannel Corona Pulse-Height Analysis," IEEE Trans. Elect. Insul., EI-8 1 (1973).

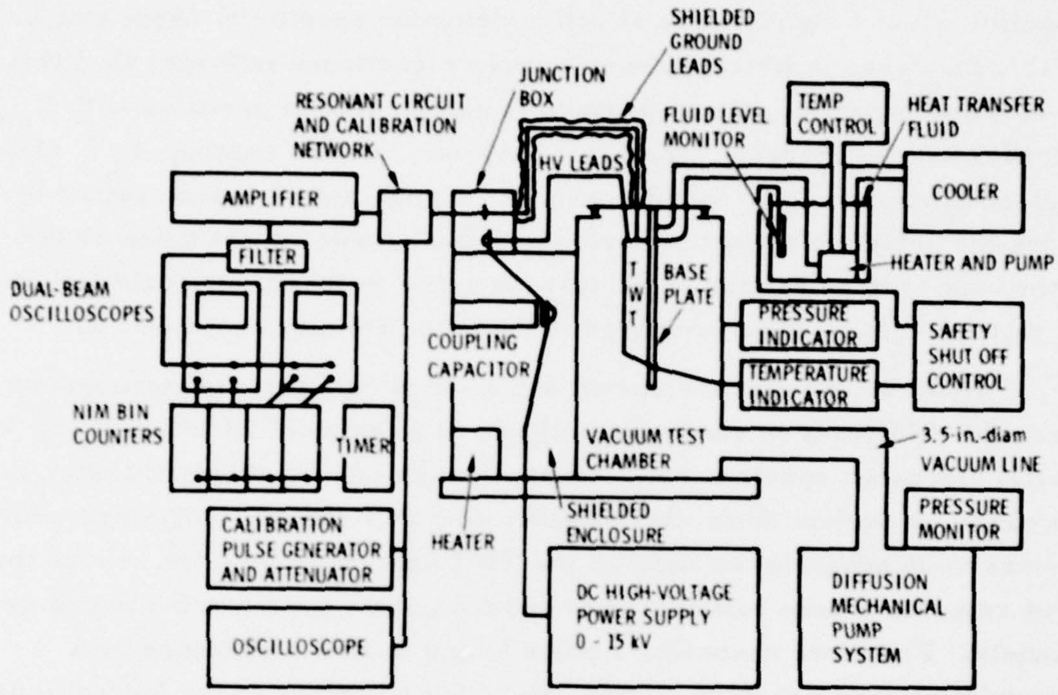


Fig. 4. Partial-Discharge Detection System for Traveling-Wave-Tube Tests

of the aluminum vacuum chamber. The TWT therefore is isolated from the grounded chamber walls. All cables from the TWT are strung through separate holes in the lucite cover, and these feedthroughs are made leak tight with Apiezon sealant. The cables are then routed to the junction box where all except those to be at high voltage are tied together and connected to the calibration and detection circuits. The ground leads between the vacuum chamber and the junction box are aluminum foil shielded to minimize radio frequency (rf) noise pick up. The high-voltage cables are kept away from the grounded enclosure and test chamber surfaces to minimize electrical stress and thereby partial discharges in these elements. These leads are then connected in the junction box to the wire from the high-voltage terminal of the coupling capacitor. The other end of this oil-filled capacitor is bolted to the wall of the shielded enclosure. This enclosure is heated to prevent moisture condensation on the high-voltage components that can cause extraneous surface discharges during tests of a TWT.

High voltage is supplied to the test circuit by means of a shielded insulated wire (RG 8 cable). The 10-Mohm blocking resistor (Figs. 2 and 3) is contained in the 0- to 15-kV dc power supply.

The signal lead from the junction box is shielded and its length minimized to eliminate noise pick up. The resonant detection circuit and the calibration network are contained in a terminal box that is attached directly to the amplifier. The amplifier, filter, oscilloscopes, and counters are connected as indicated.

A series of preset attenuators following the low-repetition-rate pulse generator provides for rapid setting of the trigger levels of the four channels in the two oscilloscopes. A third oscilloscope is used to check the amplitude and shape of the calibration pulse. The 115-V ac power lines connected to all critical equipment are from an isolated filtered source.

C. ENVIRONMENTAL TEST SUBSYSTEMS

The TWT can be PD tested at subatmospheric pressures. These lower pressures are achieved by means of a diffusion and mechanical pump system that is connected to the vacuum test chamber through a 3.5-in.-diameter glass conduit. A chamber pressure of 0.1 Torr can be attained within approximately 100 sec after initiation of pumping. Minimum pressure in the chamber is approximately 2×10^{-3} Torr after several hours of pumping.

Pressure in the chamber is monitored with two thermocouple gauges to cover the range 10^{-3} to 20 Torr. Pressures in the range 1 to 200 Torr can be monitored with a Wallace and Tiernan mechanical gauge, either at the test chamber or at the pump station. Base pressure at the pump station measured with a Veeco ion gauge is 10^{-6} Torr.

Partial-discharge tests at constant pressure in the subatmospheric range can be performed at the required pressure by reducing the conductance. However, this pressure will change during extended testing. The amount of change depends on the care taken in adjusting the low pump rate to compensate for leaks or outgassing in the system. Partial-discharge tests at varying pressures can also be conducted by appropriate pump valve adjustments. The rate at which the test chamber pressure goes through the critical range must be considered in this type of testing.

Partial-discharge tests of TWTs in gaseous environments other than air can also be performed. Argon, helium, nitrogen, or other gases can be fed into the system through a connector located on the pump station.

The TWT can be tested not only at selected pressures but also at temperatures other than ambient because it is mounted on a copper base plate whose temperature can be varied by varying the temperature of the fluid flowing through the copper tube that is brazed to this plate. (The TWT is mounted directly or through an insulating sheet to the copper plate, depending on the plate-to-ground resistance and its effect on the detection circuit resonance.) For test temperatures above ambient, only the heater is turned on in the fluid control system (Fig. 4). For temperatures below ambient, the cooler is also turned on, and the heater automatically adjusts its heating rate to maintain the specified temperature. The range of temperatures achieved with this system with the use of ethylene glycol and water (50/50 mixture) at the high end and methanol and water (also a 50/50 mixture) at the low end extends from -24 to +90°C. Temperatures within this range are controlled within 1°C. These heat-transfer fluids are covered with a nonmiscible low-vapor pressure dielectric coolant (Chevron Flo-Cool 180) to reduce evaporation.

The temperature of the TWT is monitored with a copper-constantan thermocouple connected to a direct-reading temperature indicator. The output of this indicator is connected to a safety circuit that shuts off power to the fluid control system above a preset temperature to prevent damage to the TWT from accidental overheating. A fluid level monitor is also connected to the safety circuit. A drop in fluid level will also shut off power to the fluid system.

The PD test is conducted with the component immersed in a high-strength dielectric fluid (Fluorinert FC-77) to separate internal discharges from external discharges occurring in certain TWT components, e.g., an unpotted TWT or a TWT cable. This low-viscosity dielectric fluid prevents discharges that occur on the external surfaces of the component under test, indicating that, if discharges are observed, they must be internal discharges. However, care must be taken to ensure that discharges are not occurring across the surface of the dielectric fluid. This phenomenon can be produced by the deposit of airborne contaminants or the condensation of water vapor, or both.

IV. APPLICATION OF THE AEROSPACE CORPORATION PARTIAL-DISCHARGE DETECTION SYSTEM

The Aerospace partial-discharge (PD) detection system has been used in a variety of high-voltage test measurements. These range from the investigation of discharges in simple encapsulated electrode configurations to the measurement of partial discharge spectra in fully assembled TWTs. Some of the items measured in these studies conducted with the present system or with one of the earlier developmental systems are listed below:

1. The magnitude of the discharges in mil size (10-to-20 mil diam) voids in bulk potting.
2. The inception voltage for voids in bulk potting and for voids at potting-ceramic interfaces examined as a function of void size and air pressure and for several gases.
3. The inception voltage and PD spectra for TWT cables determined by the cable configuration external to the TWT or by only the internal voids.
4. The PD spectra of partially and fully assembled TWTs as functions of test voltage, pressure, and time.
5. The PD spectra of TWTs that had passed the manufacturer's high-voltage test in relation to those that did not.
6. The partial discharge spectra of unpotted TWTs to determine their internal discharge signature.

Significant results were obtained in some of the studies and will be discussed in subsequent Aerospace reports. Some of the studies are still in progress. The objective of these studies is to determine whether the partial discharge technique can be used to identify defective TWTs, thereby eliminating the possibility of their use in space applications. Intrinsic to this objective is the establishment of the appropriate PD test procedure and pass-fail criteria to be used.

V. FUTURE TEST AND DEVELOPMENT EFFORTS

Test chamber pressure is the only environmental parameter varied in all of the partial discharge (PD) tests conducted. Although the thermal system has been set up and checked out, PD tests in which the temperature is also varied have not been conducted. This type of testing will be the next major effort in this program.

Another possible mode of PD testing that has not been conducted is long-term (days and weeks) programmed testing. This mode of testing may be essential in achieving the program objective, but it cannot be performed with the present arrangement in which the test conditions are changed by an operator and the PD counts in the various channels are manually recorded unless several operators that can be used in shifts are available. A more practical solution to this problem is to program a microprocessor to control the recording and test sequence on a long-term basis. The operation of this system can be checked and updated daily. This capability would also be beneficial in short-term tests where a great deal of time and effort is expended in changing test conditions and recording and plotting data. Design and assembly of such a microprocessor-controlled system should be the next major development effort in this program.

APPENDIX A. ANALYSIS OF PARTIAL-DISCHARGE DETECTION CIRCUIT SENSITIVITY

Several corona or partial-discharge (PD) detection systems have been proposed for TWT testing. These are the Biddle system currently in use by several TWT manufacturers, the El Rae (Bunker) system presently in the fabrication and evaluation stage, and the in-house Aerospace system in the test and development stage. These systems are basically of two types. One type (Biddle) has the detection circuit in parallel with the test sample, and the other type (El Rae and Aerospace) has the circuit in series with the test sample. The purpose of this analysis is to compare the inherent charge-voltage sensitivities of these two systems.

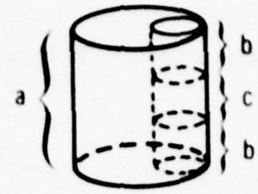
A. PARTIAL-DISCHARGE DETECTION CIRCUIT ANALYSIS

The analysis generally follows that described by Biddle.[4] A basic assumption is that the rise times of both the discharge and the calibration pulse are sufficiently short that the voltage distribution in the test circuit is determined by the circuit capacitances.

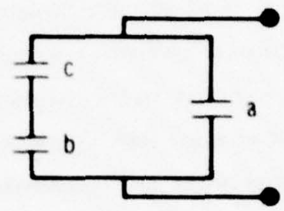
1. EQUIVALENT CIRCUIT FOR PARTIAL-DISCHARGE VOLTAGE SOURCE

The partial discharge depicted in Sketch (A) is represented by the equivalent circuit in Sketch (B), where a, b, and c are the indicated test sample capacitances. The partial discharge shorts c and produces a voltage V that causes a voltage V_a to appear across a. From Sketch (C), $V_a = [b/(a+b)]V$, i.e., the voltage appearing across a is significantly smaller than that produced by the partial discharge.

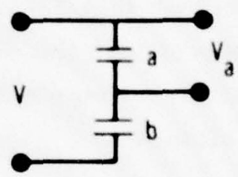
[4] Corona Detection in Systems, James G. Biddle Co., Plymouth, PA. (February 1970).



(A)

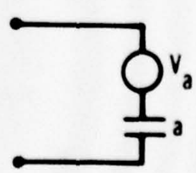


(B)



(C)

Furthermore, the charge appearing across a is also smaller than that of the partial discharge. This reduction in charge is described by $q_a = [b/(b+c)]q$.[4] The test sample with a partial discharge can be represented by the Thevenin equivalent circuit shown in Sketch (D).



(D)

This voltage source is connected to the rest of the discharge detection circuit consisting of various capacitances. The PD measurement is taken across the one that represents the equivalent input capacitances of the amplifying and monitoring circuit network.

2. DEFINITION OF DETECTION SYSTEM SENSITIVITY

Detector sensitivity as defined in ASTM Standard 1 D 1868-73 is

$$\text{Sensitivity} = \frac{\text{Amplifier Input Voltage } V_m}{\text{Terminal Corona Pulse Voltage } V_a}$$

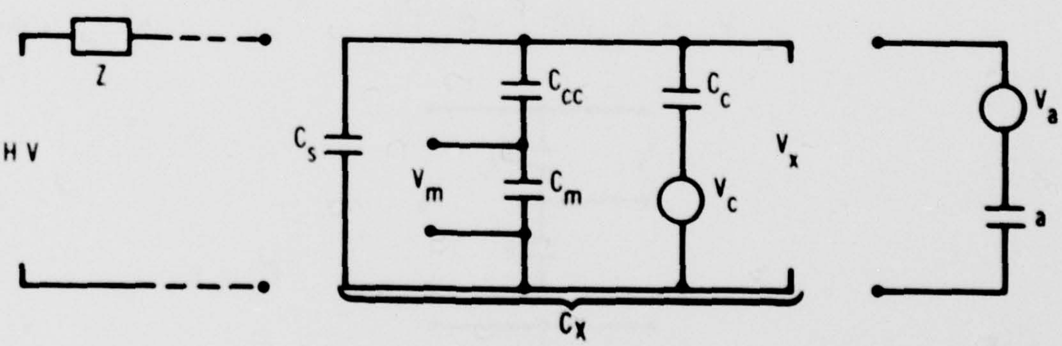
or the equivalent[1]

$$\text{Sensitivity} = \frac{\text{Charge } q_m \text{ at Amplifier Input}}{\text{Charge } q_a \text{ at Terminal of Test Sample}}$$

The detection circuit is calibrated by injecting a step-function voltage of specified magnitude across a capacitor of known value. The injected charge q_c in picocoulombs is then $q_c = C_c V_c$, where C_c is given in picofarads and V_c is in volts.

3. PARALLEL TEST CONFIGURATION

The parallel (Biddle) discharge detection circuit is shown in Sketch (E).



(E)

The high-voltage supply is isolated from the detection circuit by the blocking impedance Z. The various capacitances follow:

C_c = calibration capacitance

C_{cc} = coupling capacitance

C_m = measurement system equivalent capacitance

a = test sample capacitance = C_t, notation used in preceding sections

V_a = terminal pulsed voltage

V_c = calibration source pulsed voltage

V_x = voltage input to detection circuit

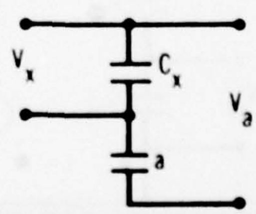
V_m = voltage input to measurement circuit

The detector circuit sensitivity V_m/V_a for the configuration shown in sketch (E) is easily determined for the representative circuit shown in Sketch (F).

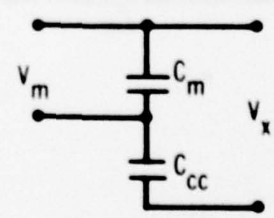
$$V_x = \frac{a}{(a + C_x)} V_a \tag{A-1}$$

where $C_x = C_s + C_c + (C_{cc}C_m)/(C_{cc} + C_m)$. Furthermore, for the circuit in Sketch (G),

$$V_m = C_{cc}/(C_m + C_{cc}) V_x \tag{A-2}$$



(F)



(G)

The combination of Eqs. (A-1) and (A-2) yields the detection circuit sensitivity V_m/V_a.

$$\frac{V_m}{V_a} = \frac{C_{cc}a}{(a + C_c + C_s)(C_{cc} + C_m) + C_{cc}C_m} \tag{A-3}$$

Equation (A-3) is the sensitivity for Circuit No. 3 in ASTM Standard D 1868-73.[1] Detector sensitivity in terms of charge can be obtained by means of

$$q_m = C_m V_m \tag{A-4}$$

and

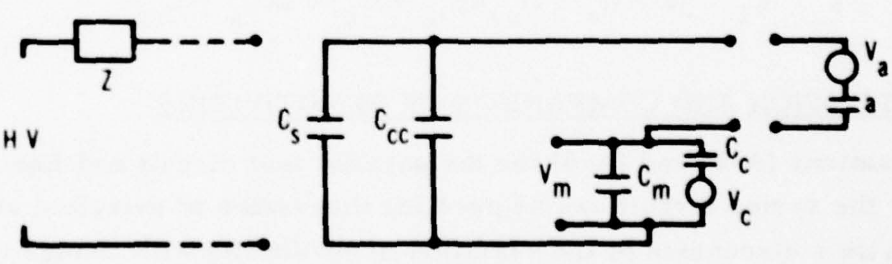
$$q_a = aV_a \tag{A-5}$$

which yields

$$\frac{q_m}{q_a} = \frac{C_m C_{cc}}{(a + C_c + C_s)(C_{cc} + C_m) + C_{cc}C_m} \tag{A-6}$$

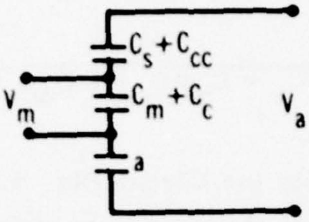
4. SERIES TEST CONFIGURATION

The series test configuration (El Rae and Aerospace) is shown in Sketch (H).

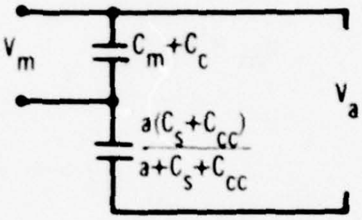


(H)

Circuit sensitivity is determined as indicated by the simplified circuits shown in Sketches (I) and (J).



(I)



(J)

which yields

$$\frac{V_m}{V_a} = \frac{a(C_s + C_{cc})}{(a + C_s + C_{cc})(C_m + C_c) + a(C_s + C_{cc})} \qquad \text{(A-7)}$$

Equation (A-7) is the sensitivity for Circuit No. 2 in ASTM Standard D 1868-73.[1] Substitution of Eqs. (A-4) and (A-5) yields the sensitivity in terms of charge.

$$\frac{q_m}{q_a} = \frac{C_m(C_s + C_{cc})}{(a + C_s + C_{cc})(C_m + C_c) + a(C_s + C_{cc})} \qquad \text{(A-8)}$$

B. DISCUSSION AND COMPARISON OF SENSITIVITIES

Equations (A-3) and (A-6) for the parallel test circuit and Eqs. (A-7) and (A-8) for the series circuit can be used for discussion of detection sensitivity. However, in a discussion of the variation in sensitivity with change in test sample capacitance a, Eqs. (A-6) and (A-8), which indicate q_m/q_a, should be used rather than Eqs. (A-3) and A-7), which describe V_m/V_a, because V_a explicitly is a function of a.

1. GENERAL CHARACTERISTICS

The following general characteristics are observed in the expressions obtained for detection sensitivity. The high-voltage lead-to-ground stray capacitance C_s must be minimized for high-detection sensitivity. Dependence of sensitivity on C_s can be eliminated if $C_s \ll C_c^a$ in the parallel circuit case and if $C_s \ll C_{cc}^a$ in the series case. In practice, C_s can usually be made to be negligible by proper arrangement of the circuit elements.

In both circuits, sensitivity decreases with an increase in test sample capacitance, a being in the denominator in both Eqs. (A-6) and (A-8). For small a, the series charge sensitivity is higher than the parallel charge sensitivity. At large a, the two charge sensitivities are comparable.

For small values of coupling capacitance C_{cc}, the series circuit is more sensitive than the parallel circuit. For large values, the two sensitivities are almost equal. Furthermore, sensitivity increases with increase in C_{cc} in both circuits, approaching a finite limit for large C_{cc}. Therefore, if C_{cc} is initially very large, it can be reduced without significantly affecting the sensitivity to reduce damage to the test sample in case total breakdown of the test sample occurs. However, if C_{cc} is severely reduced, sensitivity will also be reduced. If a large impedance is inserted to protect the test sample, sensitivity will be greatly reduced because this insertion has the effect of removing C_{cc} from the circuit and replacing it with the stray capacitance.

2. QUANTITATIVE COMPARISONS

The general characteristics are supported by a quantitative evaluation of Eqs. (A-6) and (A-8). Sensitivity is plotted as a function of test sample capacitance $a = C_t$ in Fig. A-1. Alternatively, sensitivity is plotted as a function

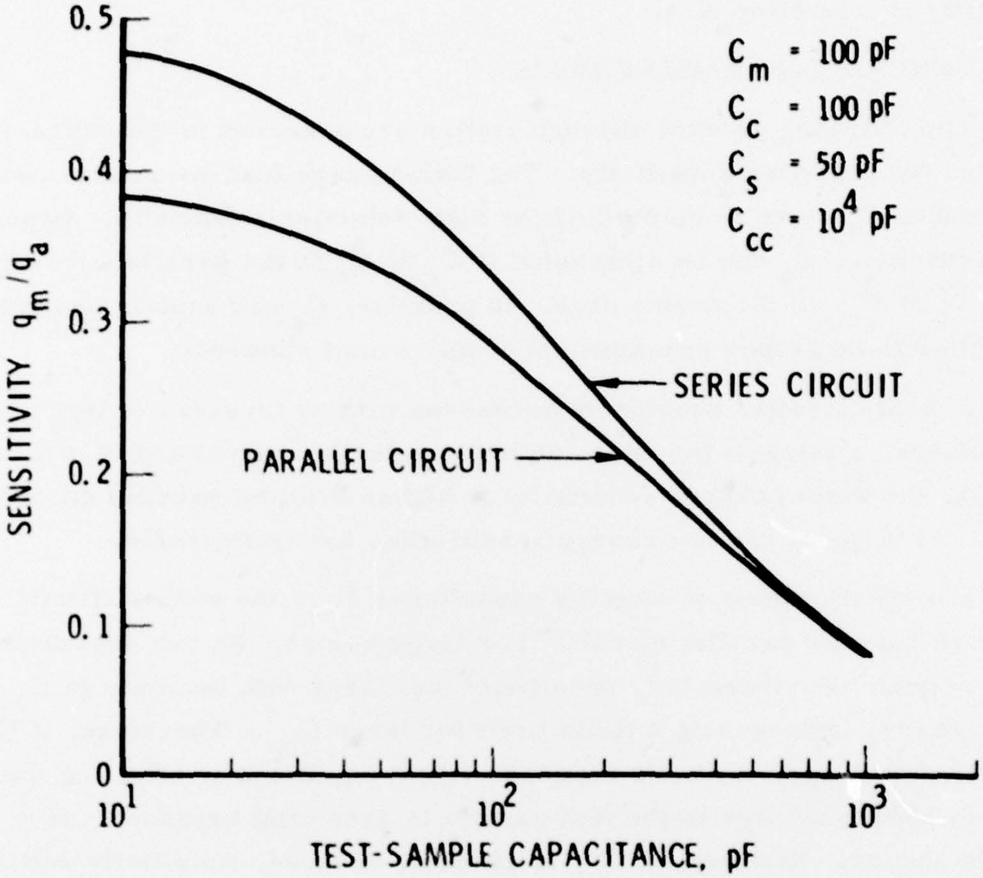


Fig. A-1. Circuit Sensitivity Versus Test-Sample Capacitance of the coupling capacitance C_{cc} in Fig. A-2. Approximate values of capacitance encountered in TWT testing are $C_m = C_c = 100$ pF, $C_s = 50$ pF, $C_{cc} = 0.01$ μF, and $a = 100$ pF.

C. PARTIAL-DISCHARGE MEASUREMENTS

Sensitivity, thus far, has been defined with respect to voltage V_m or q_m at the input to the measurement system and determined to be only a function of the capacitances of the circuit. However, the quantity that is monitored by the detection circuit operator is a voltage indicated by a deflection on the oscilloscope or a count on the pulse height discriminator. This voltage can be interpreted in terms of the terminal charge if the measurement circuit calibration is specified. For the parallel circuit shown in Sketch (E), the calibration factor is given by

$$\frac{V_c C_c}{H_c}$$

where $V_c C_c$ is the calibration charge injected into the measurement circuit, and H_c is the associated output signal voltage after amplification and processing. The terminal charge in picocoulombs, in this case, is the product of the calibration factor in picocoulomb per volt, and the observed output signal in volts.

In the series circuit shown in Sketch (H), the calibration circuit is not across the test sample, but in series with it. The terminal charge, in this case, is not the simple product indicated for the parallel circuit but one corrected to account for the terminal-calibration voltage relation

$$V_a = \frac{C_{cc} + C_s}{a + C_{cc} + C_s} V_c$$

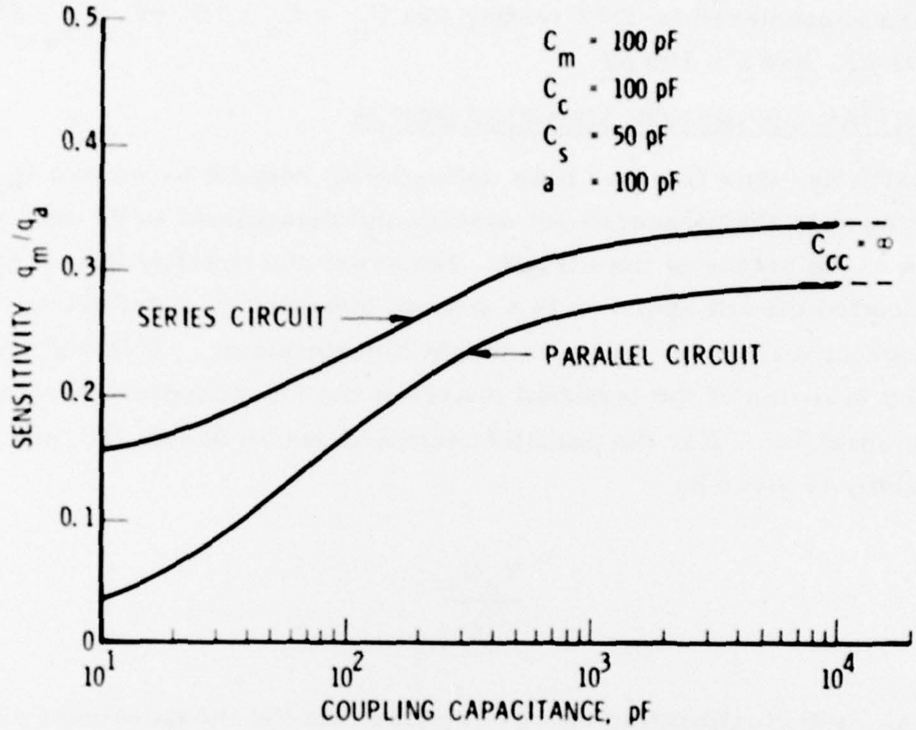


Fig. A-2. Circuit Sensitivity Versus Coupling Capacitance from the input to the measurement circuit. Therefore, the calibration factor for the series circuit is[2]

$$\frac{V_c C_c}{H_c} \frac{a + C_{cc} + C_s}{C_{cc} + C_s} \qquad \text{(A-10)}$$

The correction term on the right in Eq. (A-10) can be neglected for $C_{cc} \gg a$, a condition required for high sensitivity. Moreover, if this term cannot be neglected, C_s must be determined accurately. This measurement may be difficult.

The charge detection threshold is determined by the noise in the test circuit or the noise generated in the measurement circuit. This noise may be continuous or sporadic. The detection threshold is then given by the product of the appropriate calibration factor [Eq. (A-9) or Eq. (A-10)] and the signal voltage.

D. CONCLUSIONS

In terms of the basic sensitivity, the series detection circuit is only slightly more sensitive than the parallel circuit. (This difference is estimated at approximately 20% for the capacitances of the TWT and the other elements of the present test system.) The large differences in detection threshold between various PD detection systems arise from the variation in noise level found in these systems.

APPENDIX B. PARTIAL-DISCHARGE TEST-CIRCUIT STUDIES

A. INITIAL PARTIAL-DISCHARGE DETECTION CIRCUIT

The first partial-discharge (PD) detection circuit setup for TWT testing is schematically shown in Fig. B-1 and is essentially that given in Fig. 2. The arrangement of elements in this circuit is that specified in ASTM Standard D 1868-73 as Circuit No. 2[1] and that specified in IEEE Standard 454-1973 in Fig. F1C.[2]

The response of the circuit shown in Fig. B-1 has been analyzed [Appendix A, Eq. (A-7) and in Reference 5] and is described by

$$E_i = \frac{q}{(1 + C_m/C_{cc})C_t + C_m} e^{-(t/2RC_p)} \cos \omega t$$

$$C_p = \frac{C_t C_{cc}}{C_t + C_{cc}} + C_m$$

$$\omega = \left(\frac{1}{LC_p} - \frac{1}{4R^2C_p^2}\right)^{1/2}$$

where E_i is the input signal to the amplifier in response to a partial discharge step voltage, q is the apparent charge transfer measured across the test sample, C_m is the calibration capacitance in parallel with the input cable capacitance, and ω is the frequency of the damped oscillatory signal. E_i is directly proportional to q and increases as C_t decreases or C_{cc} increases. This variation and the effect of stray capacitance are discussed in greater detail in Appendix A. The frequency ω is dependent on both C_t and C_m, indicating that the resonance frequency will change if either the test sample or the calibrating capacitor is changed.

---

[5] F. H. Kreuger, Discharge Detection in High Voltage Equipment, American Elsevier Publishing Co., New York (1965).

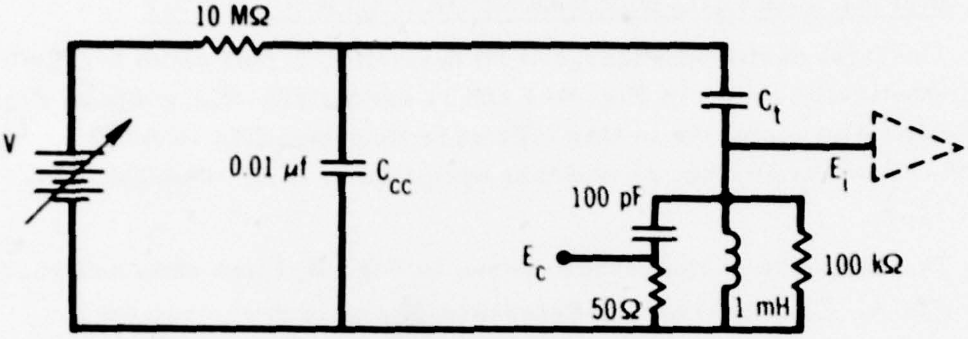


Fig. B-1. Initial Partial-Discharge Detection Circuit

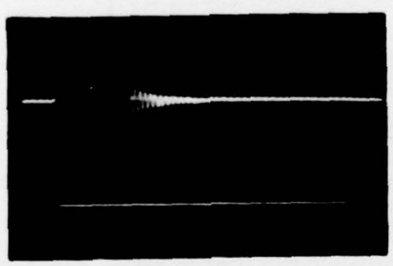


Fig. B-2. Resonant Signal Excited by Step Potential. Signal output, 2 V/div; calibration pulse, 10 mV/div; time, 20 µsec/div.

After amplification and filtering, the signal that appears at the input to the four channels (Fig. 2) is shown in Fig. B-2. This simulated signal excited as prescribed in Reference 2 exhibits a slow rise in the wave-form envelope produced by filtering at the resonance frequency. For circuit values of $L = 10^{-3}$ H, $C_t = 10^{-10}$ F, $C_{cc} = 10^{-8}$ F, $C_m = 10^{-10}$ F, and $R = 10^5$ ohm the resonance frequency given by the equation above is

$$f = \frac{1}{2\pi}\omega \simeq \frac{1}{2\pi}\left(\frac{1}{LC_p}\right)^{1/2} = 356 \text{ kHz}$$

which is in agreement with the frequency (~350 kHz) observed in Fig. B-2.

An attempt to apply this circuit, which has been used successfully to monitor low level discharges, in the detection of high-level discharges was made by changing the 100 pF calibration capacitor in Fig. B-2 to one of 1000 pF and increasing the peak calibration voltage to 500 V, thereby producing a calibration charge signal corresponding to 500 nC. This modified system then was used to detect high-level discharges in a TWT section that had exhibited a high-voltage defect. This attempt was unsuccessful. The defective section under specific conditions apparently completely broke down, placing kilovolt potentials across the resonant network, damaging the 1-mH choke and thereby severely changing the calibrated response of the system. Neon bulbs were inserted to prevent this damage and change. However, firing of these neon bulbs so distorted the discharge waveform that the resonant network was improperly excited with the result that the discharge was not registered on the appropriate counters. Another approach to the measurement of high-level discharges then was taken.

B. RESISTANCE-CAPACITANCE PARTIAL DISCHARGE NETWORK

This approach, hurriedly undertaken, consisted of removing the highly vulnerable 1-mH choke and inserting a 1-Mohm resistor (Fig. B-3). The resistor reduces the voltage across the RC network and at the input to the

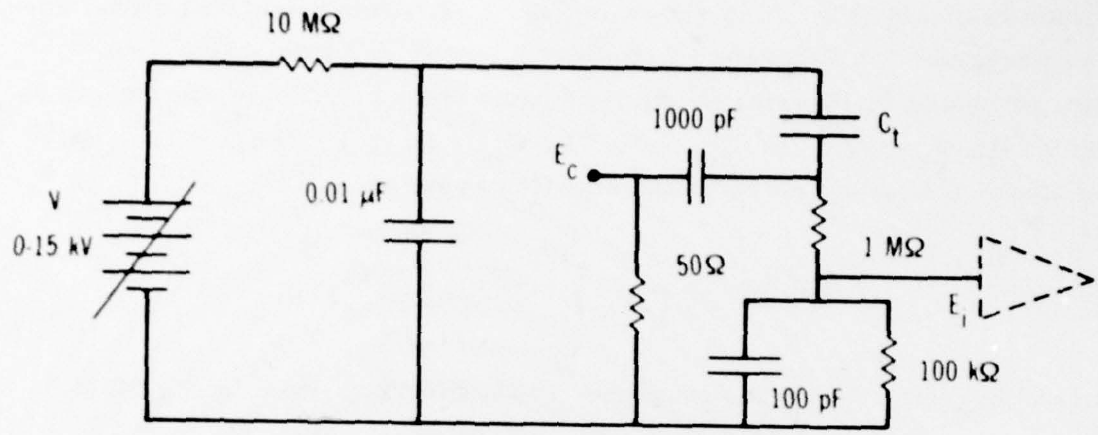


Fig. B-3. Resistance-Capacitance Partial-Discharge Detection Circuit

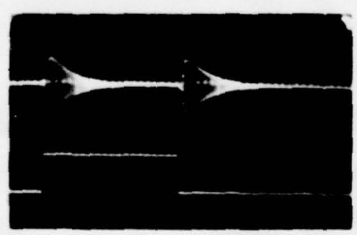


Fig. B-4. Resonant Oscillations Excited by Fast Rise and Fall Pulse. Signal output, 5 V/div; calibration pulse, 10 mV/div; time, 50 μsec/div; rise time, 0.5 μsec; fall time, 0.5 μsec.

amplifier. Instead of exciting a damped resonant oscillation, a discharge in the sample in this case produces a fast rise, singly peaked pulse. The entire system was then calibrated by means of an available Aerospace designed pulser with pulse rise time less than 1 μsec and a decay time of approximately 6 μsec. This system was used to monitor the high-level discharges occurring in the defective TWT.

Posttest examination of this detection system indicated that the calibrated levels were in error. These errors were traced to the fall time of the calibration pulse (a few μsec), which was too short relative to the rise time of the RC network (~0.1 msec). An estimate of the magnitude of this error was made by comparing the signal input to the amplifier produced by a step potential E_c with that produced by a decaying potential $E_c e^{-t/\tau'}$, the latter simulating the rapid fall of the Aerospace pulser pulse. For the step potential, the input signal is given by

$$E_i = E_c \frac{R}{R + R'} (1 - e^{-t/\tau})$$

where R = 100 kohm, R' = 1 Mohm, C = 100 pF, and $\tau = CRR'/(R + R') \simeq 9 \times 10^{-6}$ sec. From this expression, the input signal to approach full value the decay of the calibration pulse should be many times τ. For the case of the decaying potential, the input signal is given by

$$E_i' = E_c \frac{R}{R + R'} \frac{1}{(\tau/\tau' - 1)} (e^{-t/\tau} - e^{-t/\tau'})$$

where τ' is the decay time constant. In the case of the Aerospace pulser, $\tau' = 2$ μsec. A comparison of the maximum values given by these two above expressions for $\tau = 9$ μsec and $\tau' = 2$ μsec indicates that

$$\frac{E'_{i_M}}{E_{i_M}} = \frac{E_i'(dE_i/dt = 0)}{1} = 0.14$$

This result, experimentally confirmed, indicates that the levels set with the Aerospace pulser were approximately a factor of 10 low. Instead of monitoring only discharges exceeding 250 nC in the highest channel, discharges above 25 nC occurring in the defective TWT would also have been detected. This error in calibration does not invalidate the results that confirm the high-voltage defect because the actual charge transfers were directly measured and shown to be in the microcoulomb range, substantially above the 250 nC level.

The requirement that the fall time of the calibration pulse be long, i.e., greater than 1 msec, is significantly reduced if the RC detection circuit is replaced by a resonant RLC circuit. In this case, the fall time need only be longer than the resonance period. For a resonance frequency in the kilohertz range, a fall time longer than approximately 10 μsec is required. As indicated in Fig. 2, the detection circuit in the present Aerospace system is a RLC network.

C. EFFECT OF CALIBRATION PULSE SHAPE

The effect of the shape of the calibration pulse on excitation of the resonant oscillation is clearly shown by use of a commercial pulse generator with variable rise and fall times and pulsewidth. The effect of a square pulse with fast (<0.5 μsec) rise and fall is the generation of two resonant pulses, one 180 deg out of phase with respect to the other (Fig. B-4). Increasing the fall time to 5 μsec results in a single pulse (Fig. B-5); shortening of this excitation pulse does not change this single pulse. However, if the fall time is kept at 0.5 usec, the resonant pulse amplitude and shape will vary as the pulsewidth is shortened, depending on the relative phase of the two excited oscillations. In the limit of very narrow pulsewidth (<1/4 period), the excited amplitude becomes very small. The fall time of the calibration pulse therefore must be at least several times the oscillation period to avoid this problem.

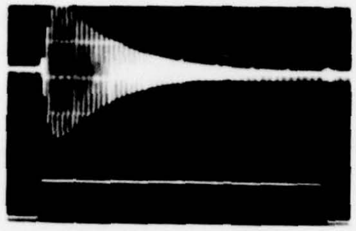


Fig. B-5. Resonant Oscillations Excited by Fast Rise and Slow Fall Pulse. Signal output, 2 V/div; calibration pulse, 10 mV/div; time, 20 μsec/div; rise time, 0.5 μsec; fall time, 5.0 μsec.

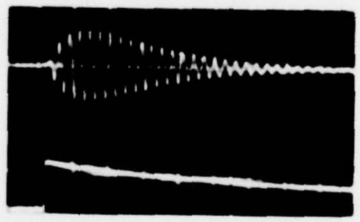


Fig. B-6. Resonant Pulse Excited by High-Voltage Pulser. E_o (signal output), 5 V/div; E_c (calibration pulse), 200 V/div; time, 10 μsec/div; C_c, 1000 pF; q_c, 250 nC.

The commercial pulse generator, limited to a peak output voltage of 5 V, could be used only in the calibration of the low-level circuit shown in Fig. 2. A high-voltage pulse circuit (peak voltage > 250 V) was designed and assembled for calibration of the high-level circuit given in Fig. 3. The calibration pulse produced by this unit has a fast rise and slow fall, well within the requirements indicated above, and is shown in Fig. B-6 along with the excited resonant pulse. This new unit with appropriate attenuation is also used for calibration of the low-level circuit.

THE IVAN A. GETTING LABORATORIES

The Laboratory Operations of The Aerospace Corporation is conducting experimental and theoretical investigations necessary for the evaluation and application of scientific advances to new military concepts and systems. Versatility and flexibility have been developed to a high degree by the laboratory personnel in dealing with the many problems encountered in the nation's rapidly developing space and missile systems. Expertise in the latest scientific developments is vital to the accomplishment of tasks related to these problems. The laboratories that contribute to this research are:

Aerophysics Laboratory: Launch and reentry aerodynamics, heat transfer, reentry physics, chemical kinetics, structural mechanics, flight dynamics, atmospheric pollution, and high-power gas lasers.

Chemistry and Physics Laboratory: Atmospheric reactions and atmospheric optics, chemical reactions in polluted atmospheres, chemical reactions of excited species in rocket plumes, chemical thermodynamics, plasma and laser-induced reactions, laser chemistry, propulsion chemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, photosensitive materials and sensors, high precision laser ranging, and the application of physics and chemistry to problems of law enforcement and biomedicine.

Electronics Research Laboratory: Electromagnetic theory, devices, and propagation phenomena, including plasma electromagnetics; quantum electronics, lasers, and electro-optics; communication sciences, applied electronics, semiconducting, superconducting, and crystal device physics, optical and acoustical imaging; atmospheric pollution; millimeter wave and far-infrared technology.

Materials Sciences Laboratory: Development of new materials; metal matrix composites and new forms of carbon; test and evaluation of graphite and ceramics in reentry; spacecraft materials and electronic components in nuclear weapons environment; application of fracture mechanics to stress corrosion and fatigue-induced fractures in structural metals.

Space Sciences Laboratory: Atmospheric and ionospheric physics, radiation from the atmosphere, density and composition of the atmosphere, aurorae and airglow; magnetospheric physics, cosmic rays, generation and propagation of plasma waves in the magnetosphere; solar physics, studies of solar magnetic fields; space astronomy, x-ray astronomy; the effects of nuclear explosions, magnetic storms, and solar activity on the earth's atmosphere, ionosphere, and magnetosphere; the effects of optical, electromagnetic, and particulate radiations in space on space systems.

THE AEROSPACE CORPORATION
El Segundo, California